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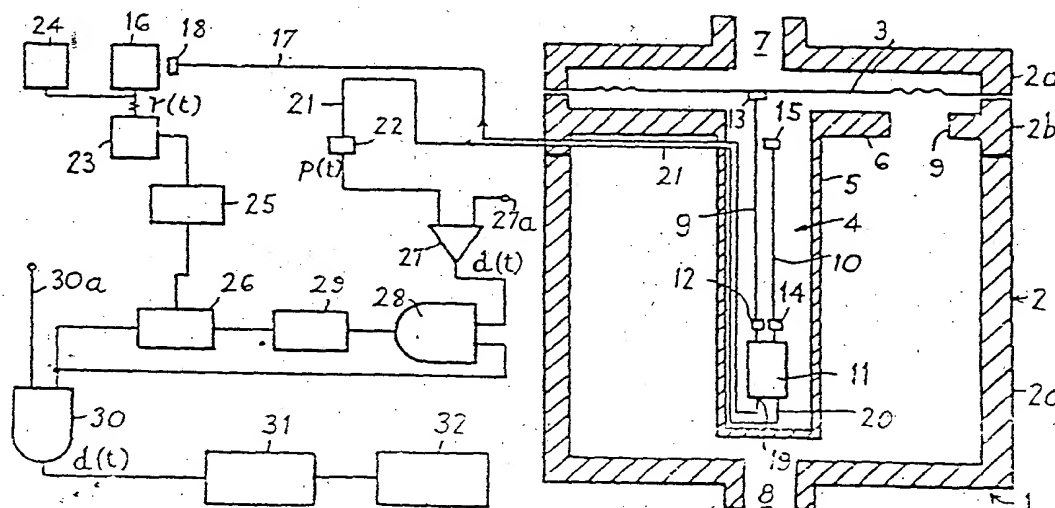
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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

<p>(51) International Patent Classification⁴ : G01L 11/00 <i>VII</i> 51D 5/26</p>	<p>A1</p>	<p>(11) International Publication Number: WO 85/ 04473 (43) International Publication Date: 10 October 1985 (10.10.85)</p>
<p>(21) International Application Number: PCT/GB85/00136 (22) International Filing Date: 1 April 1985 (01.04.85) (31) Priority Application Number: 8408383 (32) Priority Date: 31 March 1984 (31.03.84) (33) Priority Country: GB (71) Applicant (for all designated States except US): KENT SCIENTIFIC AND INDUSTRIAL PROJECTS LIMITED [GB/GB]; Physics Laboratory, The University, Canterbury, Kent CT2 7NR (GB). (72) Inventors; and (75) Inventors/Applicants (for US only): JACKSON, David, Alfred [GB/GB]; 8 Woodland Way, Canterbury, Kent CT2 7LS (GB). CORKE, Michael [GB/US]; 1865 Brentwood Lane, Wheaton, IL 60185 (US). KERSEY, Alan, David [GB/US]; The Naval Research Laboratory, Optical Science Division, Optical Technique Branch, Code 6570, Washington, DC 20375 (US).</p>		<p>JONES, Julian, David, Clayton [GB/US]; 2 The Moorings, Conyer, Sittingbourne, Kent ME9 9HQ (GB). (74) Agents: WARREN, Keith, Stanley et al.; Baron & Warren, 18 South End, Kensington, London W8 5BU (GB). (81) Designated States: AT (European patent), BE (European patent), CH (European patent), DE (European patent), FR (European patent), GB (European patent), IT (European patent), LU (European patent), NL (European patent), SE (European patent), US. Published With international search report. Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.</p>

(54) Title: OPTICAL PRESSURE SENSING APPARATUS



(57) Abstract

Optical pressure sensing apparatus comprises an optical fibre interferometer (4) arranged to sense the movement of a pressure responsive element (3) and produce an interference signal at its output (20) which can be monitored and processed to measure changes in the pressure applied to the pressure responsive element. The interferometer comprises a signal arm (9) coupled to the pressure responsive element (3) and a fixed reference arm (10). A light source (16) supplies light to the input (19) of the interferometer via an optical fibre (17) and monitoring and processing electronics (22-32) connected to the output (20) determine the optical phase shift between the light beams propagated in the signal and reference arms (9, 10) and produce a pressure reading.

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OPTICAL PRESSURE SENSING APPARATUS

1 The present invention relates to optical
pressure sensing apparatus and, more particularly,
to such apparatus utilising the principles of an
optical fibre interferometer for sensing small pres-
5 sure induced displacements of a pressure responsive
element.

 The principles of interferometry are well
known and their application to the sensitive measure-
ment of displacements is also established. However,
10 the necessity of having to use large and heavy opti-
cal components and light sources in precise align-
ment has limited their practical application.

 An object of the present invention is to
provide a pressure sensing apparatus which employs
15 the high sensitivity of an optical fibre interfero-
meter to achieve both improved sensitivity to small
pressure changes and measurement over a large dynamic
range.

 To this end, the invention consists in an
20 optical pressure sensing apparatus characterised
by an optical fibre interferometer device arranged
to sense the movement of a resilient pressure res-
ponsive element, whereby an interference signal
produced at an output of the interferometer device
25 is responsive to change in the pressure applied
to the pressure responsive element. The latter
may be any type of resilient element employed for
pressure sensing purposes, for example, a diaphragm,
capsule or one of a selection of tubes of different
30 geometries, and an element of appropriate mechanical

-2-

1 properties is selected depending upon the particular
application.

Preferably, the interferometer device comprises individual optical fibre signal and reference
5 arms, the signal arm being mechanically or optically coupled to the pressure responsive element so that the length of the optical path defined by the signal arm changes relatively to that of the reference arm in response to movement of the pressure responsive
10 element. The signal and reference arms have equal responses to physical perturbations, such as, temperature changes, other than the desired pressure measurand and these cancel one another by the process of common mode rejection. Such apparatus therefore
15 shows negligible cross sensitivity. Moreover, once calibrated, such apparatus may be used to measure gauge pressure regardless of other environmental changes. In a preferred embodiment, the signal optical fibre is secured at or adjacent one end
20 to a fixed location on the apparatus and has its opposite end, or a portion of its length, fastened to the pressure responsive element so that it is under tension, whilst the reference optical fibre is secured at or adjacent both its opposite ends
25 to fixed locations on the apparatus. In order to compensate more fully for physical perturbations other than the measurand, the reference arm is disposed, relatively to the signal arm, in the optimum position for this purpose and to this end, may,
30 for example, also have its distal end, or a part of

-3-

1 the reference fibre, attached to a non-movable location of the pressure responsive element.

5 The interferometer may be of the Michelson or Mach Zehnder type and have an input and output coupled by coupling means to signal and reference arms which are conveniently constructed from single mode optical fibre. With the Michelson configuration, the distal ends of the signal and reference fibres are reflective so as to reflect light beams propagating in the fibres, and the distal end of the signal fibre is mechanically attached to the pressure responsive element. The coupling means is adapted to mix the reflected beams in the two fibres to produce an interference signal at the output of the interferometer. With the Mach Zehnder configuration, the input and output are disposed at opposite ends of the signal and reference fibres and a portion of the length of the signal fibre is fastened to the pressure responsive element. The output coupling means mixes the beams independently propagated in the signal and reference fibres to produce the interference signal at the output.

15 In other embodiments of the invention, the interferometer device may comprise a Fabry Perot or Polarimetric configuration, in which event the signal and reference arms, in effect, each comprise an individual interferometer of one of these types. The proximal end of each arm is coupled to an input and output via suitable coupling means, for example, a beam splitting device, which is adapted to launch

1 light into the arm and recover an interference signal
therefrom. The distal end of the signal arm may
be mechanically attached to the pressure responsive
element.

5 The apparatus may include a light source
for illuminating the interferometer device, for
example, a laser light source, and means for detecting
and processing the output signal(s) to determine
the optical phase difference or shift between light
10 beams propagated in the signal and reference arms,
which phase shift is related to a change in the
pressure applied to the pressure responsive element.
Preferably, the laser light source is coupled to
the input of the interferometer device by a single
15 mode optical fibre and the detecting and processing
means may also be coupled to the output(s) by optical
fibre, so that the pressure sensing head, itself,
has a remote installation capability.

The arrangement of the light source and
20 signal detection/processing means may be similar
to that described in our International Specification
No. W084/04385 in conjunction with a temperature
sensor. Hence, means may be provided for modulating
the laser injection current of a laser light source
25 so as to produce a moving interference pattern which
is detected at the or each output of the interfero-
meter device by a photodetector and processed to
determine the optical phase shift(s) between the
light beams propagated in the signal and reference
30 arms. The processing means may be arranged to

1 compare the laser current modulating signal with the
signal at the output of the photodetector to derive
a signal corresponding to the optical phase shift.

In order that the present invention may
5 be more readily understood, reference will now be
made to the accompanying drawings, in which:-

Figure 1 is a schematic and block circuit
diagram of one embodiment of the invention, and

Figure 2 illustrates the signal waveforms
10 occurring at various points in the circuit of Figure
1.

Referring to Figure 1, the apparatus includes
a pressure sensing head 1 which comprises a cylindri-
cal housing 2 containing a pressure responsive element
15 3, in the form of a resilient diaphragm secured across
one end of the housing, and an interferometer device
4 arranged to sense movements of the diaphragm 3.
The interferometer is housed in a tube 5 which is
supported in the housing 2 from a support plate 6
20 secured to the walls of the housing. As illustrated,
the latter may be formed in three parts 2a, 2b, 2c
to permit ready assembly of the housing with the
diaphragm and interferometer within the housing.
Differential fluid pressure is applied to the diaphragm
5 3 via ports 7 and 8 in opposite ends of the housing
and an opening 9 in the support plate 6. For example,
one of the ports 7, 8 may be connected to a source
of pressure to be monitored whilst the other port
is connected to atmosphere.

The interferometer 4 comprises optical fibre

1 signal and reference arms 9,10 disposed juxtaposed
one another and formed from single mode optical fibre.
Light is launched into the respective optical fibres,
and reflected light is recovered therefrom, by a
5 single mode fibre optic directional coupler 11 connected
to the proximal ends of the fibres, and the distal
ends of the latter may be coated to improve reflectance.
Adjacent its proximal end, the signal fibre 9 is
rigidly secured to a fixed location 12 on the support
10 tube 5 whilst its distal end is attached to the centre
of the pressure sensitive diaphragm 3 at 13 so that
the signal fibre is maintained under tension. The
reference fibre 10 is rigidly secured at or adjacent
both its proximal and distal ends to fixed locations
15 14,15 on the support tube.

Light from a single frequency semi-conductor
diode laser 16 is launched into a single mode optical
fibre 17, via an isolator 18 and is supplied to the
input 19 of the interferometer at the directional
20 coupler 11 which amplitude divides the light into
the signal and reference fibres 9,10. The resulting
optical beams propagated in the signal and reference
fibres are reflected from the distal ends of the
fibres back to the coupler 11 which coherently recom-
25 bines the light to produce an interference signal
at the output 20 of the interferometer, which signal
is monitored to recover the optical phase difference
between the signals in the two fibres from the intensity
of the recombined light signals. In the present
30 embodiment, this is achieved by using a signal processing

-7-

1 technique similar to that described in our afore-
mentioned International specification. The light
intensity is conveniently monitored by guiding the
interference signal through an optical fibre 21 to
5 a photodetector 22. The light source 16, detector
22 and signal processing electronics may therefore
be situated remotely from the pressure sensing head 1.

The signal fibre 9 is maintained under tension
such that a change in differential pressure across
10 the pressure responsive diaphragm 3 results in a
change in the length of the signal optical fibre.
Hence, by detecting and processing the interference
signal produced at the output 20 the pressure change
may be determined. In one typical example having
15 an Inconel x circular diaphragm 3 of thickness 0.102
mm (0.004") and diameter 71.1 mm (2.800") different-
ial pressure measurements in the range 0 - 100 mbar
with a resolution of 10^{-4} mbar have been achieved.
As the signal and reference fibres 9,10 are housed
20 in a similar environment, their equal responses to
physical perturbations, for example, temperature,
other than the pressure measurand, cancel one another
out by the process of common mode rejection. The
device therefore shows negligible cross sensitivity
25 and, once calibrated, does not normally require recal-
ibration for different applications or changes in
the environment in which it is used.

The signal processing system comprises an
oscillator or ramp generator 23 for modulating the
30 laser injection current which is supplied by a DC

1 cell 24 (e.g. a Ni-Cad cell), with a high frequency
ramp current. This ramping signal may have a frequency
in the range from 100 Hz - 10 kHz, e.g. 5 kHz. A
high frequency reference square wave derived from
5 the oscillator 23 via a JK flip-flop 25, which also
divides the signal by two, is supplied to one input
of the phase comparator 26.

The output from the photodiode detector
22 is connected to one input of a high gain comparator
10 27 having its other input 27a connected to a reference
voltage. The output of the comparator 27 is a square
wave and this is fed to one input of a logic AND
gate 28 having its output connected, via a JK flip-
flop 29, which divides the signal from the AND gate
15 28 by two, to the second input of the phase comparator
26. The output of the latter is connected to the
second input of the AND gate 28 and also to one input
of a second logic AND gate 30 having its other input
30a connected to receive pulses from a clock pulse
20 generator, for example, a 1 MHz generator. The signals
from the output of the gate 30 are fed, via a timer
31, to a microprocessor 32 for processing and storing.

In Figure 2, $r(t)$ and $p(t)$ show the time
variation of the optical intensity at the interfero-
25 meter output when the laser injection current is
ramp-modulated. This output is fed to the high-gain
comparator 27 and 'hard-limited' to form a series
of pulses $c(t)$. The remaining electronics measure
the time $t_1 = (\tau - \tau_D)$ where τ is the time, between
30 the start of the ramp $r(t)$ and the first negative

-9-

1 edge encountered in the photodiode output signal
p(t), and τ_D is the time delay. This time, t_1 is
directly related to the optical phase shift between
the arms 9,10 of the interferometer; t_1 is measured
5 by performing a phase comparison between the square
wave, derived from the first negative edge in the
photodiode output in each ramp period, and the reference
square wave obtained directly from the ramp generator
23. The ramp generator frequency is chosen to be
10 two orders of magnitude higher than the pressure
induced fringe drift rate so that relatively simple
decision making electronics are used to determine
when the fringe pattern corresponds to a new fringe
number. By using the 1 MHz clock an accurate determi-
15 nation of the pulse width t_1 is obtained, from which
the direction and magnitude of the pressure change
is determined. The lower two traces c(t) and d(t)
in Figure 2 show the output of the comparator 27
in the upper trace and the input of the microcomputer
20 32 in the lower trace.

Whilst a particular embodiment has been
described, it will be understood that modifications
can be made without departing from the scope of the
invention as defined by the appended claims. For
5 example, the interferometer 4 may be constructed
in a Mach Zehnder configuration instead of the Michel-
son arrangement illustrated. In this event, the
optical fibre signal arm 9 has a portion of its length
fastened along the surface of the diaphragm 3 and
the input and outputs are at opposite ends of the

1 signal and reference arms. In other embodiments,
the signal and reference arms 9,10 may each be formed
as a Fabry Perot or Polarimetric interferometer with
the light being launched into and recovered from
5 the proximal ends of the interferometers via associated
beam splitting devices. With the Fabry Perot configura-
tion, the light may be supplied to the signal and
reference arms via fibre optic leads which are connected
to the fibre optic arms by reflective splices. With
10 the Polarimetric configuration, the signal and reference
arms are made from birefringent fibre. In either
of the latter two embodiments, signal processing
systems similar to that illustrated in Figure 1 may
be connected to each arm and the outputs from the
15 two systems may be compared to produce a pressure
measurement signal which is substantially independent
of changes in other environmental conditions in
which the pressure sensing head 1 is used.

-11-

CLAIMS

- 1 1. Optical pressure sensing apparatus characterised
by an optical fibre interferometer device (4) arranged
to sense the movement of a resilient pressure responsive
element (3), whereby an interference signal produced
5 at an output (20) of the interferometer device is
responsive to changes in the pressure applied to
the pressure responsive element.
2. Apparatus according to claim 1, characterised
in that the interferometer device (4) comprises an
10 optical fibre signal arm (9) and an optical fibre
reference arm (10), the signal arm being mechanically
or optically coupled to the pressure responsive element
(3) so that the length of the optical path defined
by the signal arm changes relatively to that of the
15 reference arm in response to movement of the pressure
responsive element.
3. Apparatus according to claim 2, characterised
in that the interferometer device is of the Michelson
or Mach Zehnder type and comprises an input (19)
20 and output (20) coupled by coupling means (11) to
the signal and reference arms (9,10), which are pre-
ferably constructed from single mode optical fibre.
4. Apparatus according to claim 1 or 2, characterised
in that the interferometer device (4) comprises a
5 Fabry Perot or Polarimetric configuration in which
the signal and reference arms (9,10) each comprise
an optical fibre interferometer of one of these con-
figurations, each arm (9,10) being coupled to an
input and an output via coupling means which is adapted
to launch light into the arm and recover reflected

- 1 light therefrom to produce an interference signal
- at the associated output.
5. Apparatus according to claim 3 or 4, characterised
in that the signal arm (9) has its proximal end adja-
5 cent the coupling means (11) secured to a fixed lo-
cation (12) and its distal end (13) attached to the
pressure responsive element (3), and in that the
reference arm (10) is secured at or adjacent both
its proximal and distal ends to fixed locations (14,15)
10 the distal ends of the signal and reference arms
being reflective.
6. Apparatus according to any preceding claim, charac-
terised by a light source (16) coupled to the input
(19) of the interferometer device via a single mode
15 optical fibre (17).
7. Apparatus according to any preceding claim, charac-
terised by means (22-32) for detecting and processing
the output(s) (20) of the interferometer device to
determine the optical phase shift between light beams
20 propagated in the signal and reference arms (9,10),
which phase shift is responsive to change in the
pressure applied to the pressure responsive element
(3), said detecting and processing means being coupled
to the output(s) (20) by optical fibre (21).
- 25 8. Apparatus according to claim 7, characterised
by a laser light source (16) for illuminating the
interferometer device (4) and means (23) for modulating
the laser injection current to produce an interference
signal at the or each output (20) in the form of
30 a moving interference pattern.

-13-

- 1 9. Apparatus according to claim 8, characterised
in that the modulating means (23) modulates the bias
injection current of the laser with a ramp signal
to produce a linearly moving interference pattern
5 at the or each output (20) of the interferometer
device.
- 10 10. Apparatus according to claim 8 or 9, characterised
in that the processing means compares the laser current
modulating signal with the signal at the output (20)
of the interferometer device to derive a signal corres-
ponding to the optical phase shift.

INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 85/00136

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) *		
According to International Patent Classification (IPC) or to both National Classification and IPC		
IPC ⁴ : G 01 L 11/00; G 01 L 1/24; G 01 D 5/26		
II. FIELDS SEARCHED		
Minimum Documentation Searched ⁷		
Classification System	Classification Symbols	
IPC ⁴	G 01 L G 01 D	
Documentation Searched other than Minimum Documentation to the extent that such Documents are included in the Fields Searched *		
III. DOCUMENTS CONSIDERED TO BE RELEVANT⁸		
Category *	Citation of Document, ¹¹ with indication, where appropriate, of the relevant passages ¹²	Relevant to Claim No. ¹³
X	Patent Abstracts of Japan, volume 5, nr. 185, (P-91) (857), 25 November 1981 & JP, A, 56112608	1-3
X	DE, A, 3031961 (LICENTIA PATENT-VERWALTUNGS GmbH) 11 March 1982, see figures 1-3; introduction; page 4, line 33 - page 7, line 23; page 9, lines 4-17	1-5,7
X	EP, A, 0021199 (TOKYO SHIBAURA DENKI, K.K.) 7 January 1981, see figures 2,3,12; page 14, line 19 - page 17, line 30	1-10
A	EP, A, 0013974 (ROCKWELL INTERNATIONAL CORP.) 6 August 1980, see figures 1,3,4,5; page 5, line 1 - page 6, line 9; page 10, line 1 - page 14, line 2	1-3,6,7

* Special categories of cited documents: ¹⁰

"A" document defining the general state of the art which is not considered to be of particular relevance

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V. CERTIFICATION

Date of the Actual Completion of the International Search
27th June 1985

Date of Mailing of this International Search Report
26 JUL 1985

International Searching Authority

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Signature of Authorized Officer

J. O. G. L. M. Kruidenberg

III. D CUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

Category *	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
A	Elektronik, volume 31, nr. 12, June 1982; (München, DE) J. HESSE; W. SOHLER: "Faseroptische Sen- soren", pages 89-92 see page 89, paragraphs 2,3; (3.1,3.4); figures 1,3,4,5	1-4

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON

INTERNATIONAL APPLICATION NO.

PCT/GB 85/00136 (SA 9143)

This Annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report. The members are as contained in the European Patent Office EDP file on 17/07/85

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
DE-A- 3031961	11/03/82	None	
EP-A- 0021199	07/01/81	JP-A- 55164995	23/12/80
		US-A- 4334781	15/06/82
		JP-A- 56002095	10/01/81
EP-A- 0013974	06/06/80	JP-A- 55099018	28/07/80
		US-A- 4329058	11/05/82

